

Heating of the cooling flow

The feedback effervescent heating model

Nasser Mohamed Ahmed¹

National Research Institute of Astronomy and Geophysics (NRIAG), El-Marsed Street, 11421 Helwan, Cairo, Egypt

ABSTRACT

The standard cooling flow model has predicted a large amount of a cool gas in the clusters of galaxies. The failure of the Chandra and XMM-Newton telescopes to detect a cooling gas (below 1-2 keV) in the clusters of galaxies has suggested that some heating process must work to suppress the cooling. The most likely heating source is the heating by AGNs. There are many heating mechanisms, but we will adopt the effervescent heating model which is a result of the interaction of the bubbles inflated by AGN with the intra-cluster medium(ICM).

Using the FLASH code, we have carried out 1D- time dependent simulations to investigate the effect of the heating on the suppression of the cooling in cooling flow clusters. We have found that the effervescent heating model can not balance the radiative cooling and it is an artificial model. Furthermore, the effervescent heating is a function of the ICM pressure gradient but the cooling is proportional to the gas density square and square root of the gas temperature.

Key words. Heating – Effervescent Heating Model – cooling flow – black hole

1. Introduction

According to the steady flow assumption of the standard cooling flow model, we must find a cool gas and a multi-phase medium within the cooling core in clusters of galaxies which are not observed in any wavebands (X-ray and non X-ray). This is known as the cooling flow problem in clusters of galaxies. In others words, there is a discrepancy between standard cooling flow model and observations (X-ray and non X-ray). This strong discrepancy is interpreted as either the gas is being prevented from cooling by some heating process, or it cools without any spectroscopic signature (Fabian et al. 2001) which is difficult. But, we see that this discrepancy between the standard cooling flow model and X-ray observations indicates that either the cooling in the center of cooling flow clusters must be suppressed by any heating mechanism, or the steady flow assumption of the standard cooling flow model is not appropriate. Somewhere else, we have concentrated in the second point which it is found that the steady flow with cooling is impossible, i.e the cooling flow problem is due to the wrong steady flow assumption. In this work we will concentrate in the first point, heating the cooling flow.

The failure of the multi-phase model has revived the idea of a heating mechanism which can suppress the cooling. There are five main conditions for the heating (see Gardini & Ricker 2004, for review) :

1. The heating must be fine tuned and distributed to get the smooth observed temperature profile. Too much heating would result a outflow from the center region. Too little heating is not sufficient to suppress the cooling. Moreover, the heating process must be self regulated: the mass flow rate triggers the heating and the heating reduces the mass flow

rate (Böhringer et al. 2002). That mechanism is called a heating with a feedback.

2. The heating mechanism by AGN must be sporadic because the radio activities are not observed in every cooling flow clusters.
3. The kinetic energy injection must be subsonic and the ICM must not be shocked, as observed in general case. The shock could compress the gas producing the catastrophic cooling much faster.
4. The heating mechanism must preserve the observed entropy profiles of the ICM, which decrease toward the center.
5. The heating must not destroy the metallicity profiles which are peaked toward the centers (Tamura et al. 2002; De Grandi & Molendi 2001; Irwin & Bregman 2001).

A giant elliptical or cD galaxy sits at the potential well of every cooling flow cluster (Mathews et al. 2003; Eilek 2004). The popular heating mechanisms are a heating by AGN (Binney & Tabor 1995; Tabor & Binney 1993; Brüggén & Kaiser 2002), thermal conduction, cosmic rays, galaxies motions, magnetic field reconnection (Soker & Sarazin 1990) and turbulent mixing (Kim & Narayan 2003). About 71 percent of the cDs in the cooling flow clusters are radio loud compared to only 23 percent of non-cooling flow clusters (Burns 1990). This result suggests that there a relationship between the AGN activities and the presence of cooling flow.

In some of cooling flow clusters, the recent X-ray observations reveal holes in the X-rays surface brightness coincident with the radio lobes, known as X-ray cavities or bubbles (see Fabian et al. 2006, as example). The bubbles or cavities are not

a universal phenomenon, suggesting a duty cycle. Radio sources are not even detected in some cooling-flow clusters.

The observed metallicity gradients make a constraint on the ability of bubbles to mix the ICM (Böhringer et al. 2004). Brighenti & Mathews (2002) have run many 1D simulations of clusters with various levels of heating. They concluded that the best fit of temperature profiles with the real clusters is without heating. The AGNs are assumed to inject buoyant bubbles into the ICM, which heat the ambient medium by doing work PdV as they rise and expand. This mechanism is called the effervescent heating model or mechanism (Begelman 2001). In this work, we will concentrate on this mechanism, using time dependent hydrodynamics simulations, FLASH code (Fryxell et al. 2000).

2. Effervescent heating model

The center AGN is assumed to inflate bubbles of relativistic plasma in the ICM. These bubbles will expand as they rise, doing PdV work on their surroundings. *Assuming a steady state and spherical symmetry*, the energy available for heating the ICM known as the effervescent heating (Begelman 2001; Ruszkowski & Begelman 2002) is:

$$\dot{E} \propto P_b(r)^{(\gamma_b-1)/\gamma_b},$$

where P_b is the partial pressure of buoyant fluid inside the bubbles at radius r , and γ_b is the adiabatic index of buoyant fluid. Begelman (2001) and Ruszkowski & Begelman (2002) have assumed that the pressure of a buoyant fluid is scaled with the thermal pressure of the ICM; i.e. the ratio between the pressure of a buoyant fluid and the thermal pressure of the ICM is a constant with radius. In this case:

$$\dot{E} \propto P(r)^{(\gamma_b-1)/\gamma_b}$$

In that model, we should note that the heating profile by AGN is proportion to the ICM properties, not the AGN itself. The heating rate per unit volume is given by:

$$\mathcal{H}_v \approx -h(r) \nabla \cdot \frac{\dot{E}}{4\pi r^2} = -h(r) \left(\frac{P}{P_o} \right)^{(\gamma_b-1)/\gamma_b} \frac{1}{r} \frac{d \ln P}{d \ln r}, \quad (1)$$

where \mathcal{H}_v is heating rate ($\text{erg cm}^{-3} \text{ Sec}^{-1}$), P_o is the center pressure and $h(r)$ is a normalization function multiplied by a cut-off function $(1 - e^{-r/r_o})$ as proposed by Ruszkowski & Begelman (2002) :

$$h(r) = \frac{L}{4\pi r^2} q^{-1} \times (1 - e^{-r/r_o}),$$

where r_o is a small cutoff radius (10-25 kpc) and L is the Luminosity of the center source which is given by:

$$L = \int_0^{r_{max}} \mathcal{H}_v dV$$

Upon reflection, the function $(1 - e^{-r/r_o})$ is not a cutoff function as proposed, but it is a *shallowness function* added to let the heating profile shallower more than the original one, working as a artificial fine tune. The function e^{-r/r_o} is working as a cutoff

function. As r_o increases, we get a shallower profile. The factor q is given by

$$q = - \int_0^{r_{max}} \left(\frac{P}{P_o} \right)^{(\gamma_b-1)/\gamma_b} \frac{1}{r} \frac{d \ln P}{d \ln r} (1 - e^{-r/r_o}) dr$$

We found that without the minus sing (not in the original paper) heating will be negative. This factor q is a normalization factor to let the total heating inside r_{max} be equal to L . By doing this normalization, we find that the presence of the term P_o (in equation 1) is not essential.

Finally, the luminosity of the central source L is given by a feedback from mass flow rate (mass accretion rate)

$$L = \epsilon \dot{M}_{flow-min} c^2$$

where ϵ is the accretion efficiency and c is the speed of light. $\dot{M}_{flow-min}$ which is given by:

$$\dot{M}_{flow-min} = (-4\pi r_{min}^2 \rho v)$$

is the mass flow rate in the inner radius r_{min} depending on the resolution of simulation. For high resolution simulation, we are aware that the mass flow rate is a small quantity which is not enough to fuel the AGN but that model is most accurate one we know. The actual heating mechanism is still unclear and uncertain.

At the end, we get the heating profile as:

$$\mathcal{H}_v = -\frac{L}{4\pi q r^2} P_b^{\frac{1}{\gamma_b}} \frac{dP}{dr} (1 - e^{-r/r_o}) \quad (2)$$

and the internal energy equation becomes:

$$\frac{\partial H_v}{\partial t} + \nabla \cdot (H_v \mathbf{v}) - \frac{dP}{dt} = -\epsilon_v + \mathcal{H}_v \quad (3)$$

where ϵ_v is the X-ray emissivity and H_v is the gas enthalpy per unit volume ($U_v + P$), and H_v is given by:

$$H_v = \frac{5}{2} \frac{k T \rho_g}{\mu m_p}$$

where ρ_g is the gas density.

2.1. Problem with the effervescent heating model

The effervescent heating profile depends on the gradient of ICM pressure rather than temperature and it is much steeper than the X-ray emissivity. This model needs a fine tuning because the velocity in the center must be a negative quantity, otherwise the gas could be accumulated somewhere near to the center. The gas will flow from outwards and inwards into that region. In other words, the feedback can not ensure the fine tuning and can cause the velocity in the center to be a positive quantity and in the other part of the cooling core to be negative.

Ruszkowski & Begelman (2002) claimed that their model does not need a fine tuned heating. We argue that their model is fine tuned by choosing some value of r_o to control the steepness of the heating profile, and choosing ϵ accretion efficiency to control the amplitude of the heating function. The accretion

efficiency is not a constant for any simulation but is allowed to change to guarantee an artificial fine tuned heating.

The scaling of the buoyant fluid pressure inside the bubbles with the ICM pressure is a difficult assumption, during the motion of bubbles in ICM. The bubbles must expand in some way to keep this ratio a constant. The free parameters (r_o , r_{max} , ϵ , and r_{min}) in the effervescent heating model are responsible for the model to be artificial and do not reflect any physics for the heating.

3. Initial conditions

The total cluster mass or the gravitation acceleration can be determined from X-ray observations by assuming that the gas is in a hydrostatic equilibrium and a spherical symmetry

$$\mathbf{g} = \frac{\nabla P}{\rho_g} \quad (4)$$

where P and ρ_g are the observed gas pressure and density. The inflowing gas has nearly no effect on the total cluster mass, then we can assume that the value of \mathbf{g} nearly does not change since the cluster started to cool.

In cooling flow clusters, the temperature and gas density profiles change only in the cooling core region due to cooling, but they do not change in the outer part of the cooling core. The cooling has no effect on the total clusters masses. We determine the initial temperature profile by fitting the observed X-ray temperature profile of the outer part of the cooling core with the universal temperature profile of Loken et al. (2002).

$$\frac{T(r)}{T_x} = T_o (1 + a_x r/r_{vir})^{-\delta} \quad (5)$$

where T_o , a_x , and δ are free parameters. For most clusters, these fitting parameters are found to be $a_x = 1, 5$, $\delta = 1.67$, and $T_o = 1.31$. Then the gas density is given by

$$\rho_g(r) = \rho_{go} \times \left(\frac{T_{go}}{T_g(r)} \times \exp \frac{\mu m_p}{k} \int_0^r \frac{g(r)}{T_g(r)} dr \right) \quad (6)$$

where ρ_g is the gas density. ρ_{go} and T_o are the gas density and temperature at the center. The $g(r)$ is obtained by current X-ray observation assuming a hydrostatic equilibrium as in equation 4.

We will take the observed X-ray gas and temperature profiles of the Chandra observation (Vikhlinin et al. 2005) as an initial conditions for the cluster A1991 as in figure 1.

3.1. Models

We have carried out four model simulations assuming the effervescent heating model. Model A is carried out only with cooling. Model B is a model with an effervescent heating and cooling and model C is the same as model B but with higher resolution (smaller value of r_{min}). Finally, the model D has a higher cutoff radius r_o to get a smoother heating profile, see table 1.

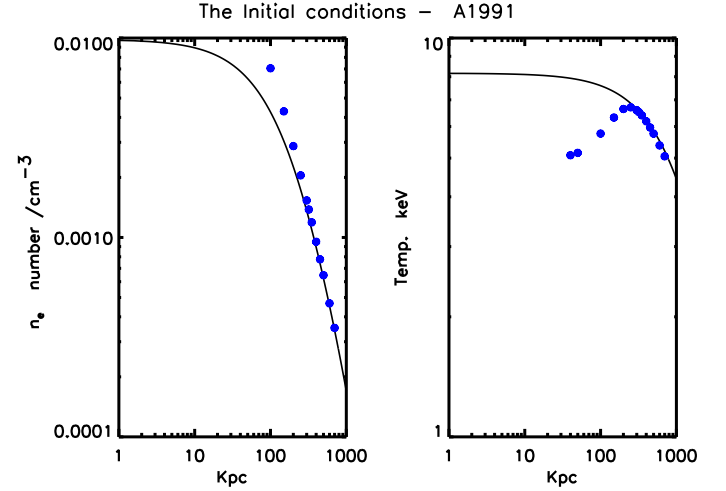


Fig. 1. Initial conditions: the dots are the observed X-ray temperature and gas density profiles (Vikhlinin et al. 2005). The solid line is the initial fitted temperature profile (Loken et al. 2002).

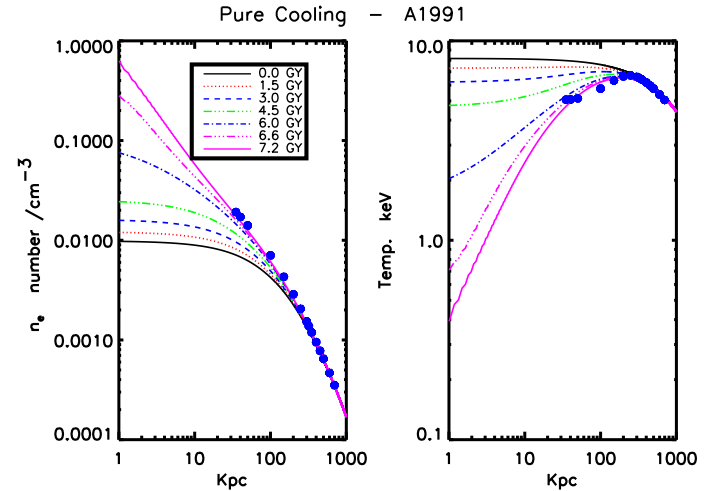


Fig. 2. Model A, pure cooling: the simulated gas density and temperature profiles at different times up to 7.2 G yr. The big dots represent the observations. The simulation agrees very well with the X-ray observation (Vikhlinin et al. 2005).

4. Results and discussion

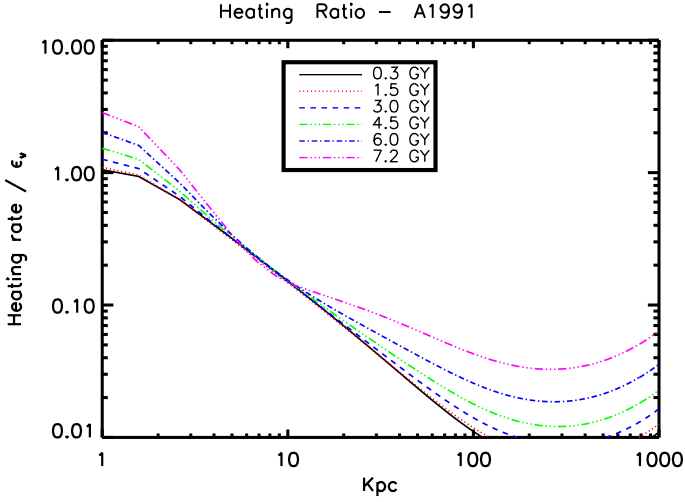
In this section, we describe our four simulations and the results will be given as follow:

4.1. Model A

The cluster A1991 is observed by the Chandra X-ray observatory (Vikhlinin et al. 2005). Model A is a time dependent pure cooling simulation, there is no heating. This simulation have run until time 7.2 Gy where the simulated temperatures and densities agree very well with the X-ray observations (Vikhlinin et al. 2005) (see figure 2). After time 7.2 Gy, the catastrophic cooling accrued only within a few cells due to the resolution, reflecting boundary conditions and steep potential profile. The heating can not help because it will heat the whole cooling core.

Table 1. The models

Model	Note	cutoff radius r_o	r_{max}	ϵ	Resolution - r_{min}
Model A	Pure Cooling	-	-	-	520 pc
Model B	Cooling and Heating	22 Kpc	2000 Kpc	.01	520 pc
Model C	Cooling and Heating	22 Kpc	2000 Kpc	.01	78 pc
Model D	Cooling and Heating	40 Kpc	2000 Kpc	.001	520 pc

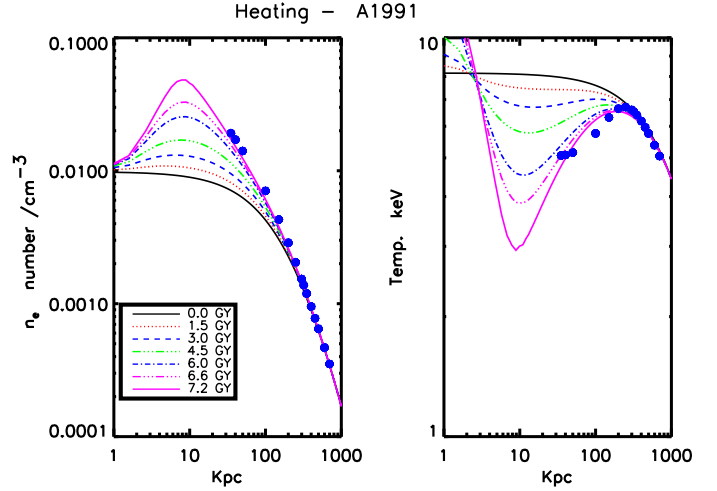
**Fig. 3.** Model B: the plot of the ratio between the heating rate and cooling rate ($\mathcal{H}_v / \epsilon_v$).

4.2. Model B

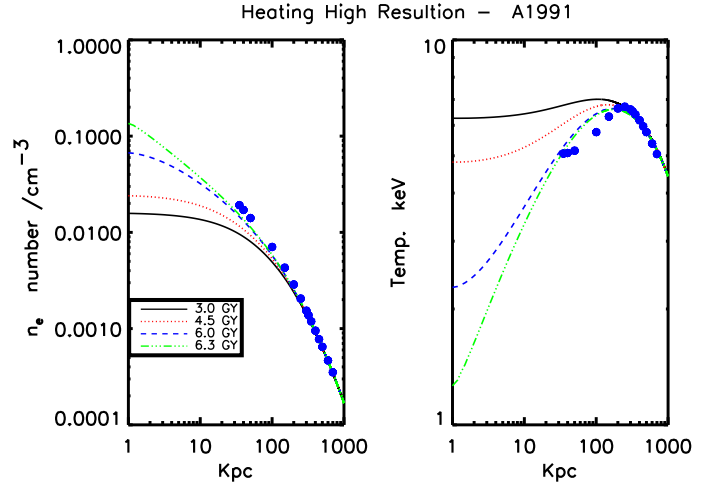
The mass accretion rate (to fuel the black hole) is taken to be equal to the mass inflow rate at the inner radius r_{min} . In this model, we have set the cutoff radius r_o and heating efficiency ϵ at 22 kpc and .01 respectively, see table 1. The resolution in the center is about 520 pc which is large than the black hole accretion radius. Ruszkowski & Begelman (2002) have chosen r_{min} equal to 1 Kpc to get large mass flow rate which can fuel the black hole in the cluster center. We are certain that at small radius the mass flow rate is not sufficient to fuel the central black hole to stop the cooling. However, that is the only way to study the effect of the heating in clusters properties. The heating profile is much steeper than the X-ray emissivity which makes it difficult for the heating profile to balance the radiative cooling. In figure 3, we plot the heating rate and cooling rate ratio. As in figure 4, the cluster center is overheated and there is no balance between the heating and cooling; that is clear in the temperature profile. Moreover, inside 10 kpc, the gas density peaks near to center not in the center which is not observed. The gas becomes a clumpy structure. There is a outflow from the cluster center.

4.3. Model C

In model B, the inner radius (resolution) is about 520 pc which is larger than the black hole accretion radius. This model is similar to model B but the resolution is higher to get smaller accretion radius (inner radius). We have set the resolution or inner radius equal to 78 pc which can not be achieved by three dimensions simulations. The result is that the heating is not enough to balance the radiative cooling because the mass flow rate at a small

**Fig. 4.** Model B: the simulated gas density and temperature profiles as functions of radius. The big dots represent the observations

radius is very small. Of course this model is more realistic than model B because of the smaller inner radius (accretion radius).

**Fig. 5.** Model C, high resolution (78 pc) and heating with cooling: the simulated gas density and temperature profiles are the same as in pure cooling simulation. The big dots represent the observations

4.4. Model D

In the model D, we set cutoff radius ($r_o = 44$ kpc) at a larger value than in model B in order to get a smoother heating profile, see table 1. The result is much better than model B but there is still a problem to fit the observations, see figure 6. The tempera-

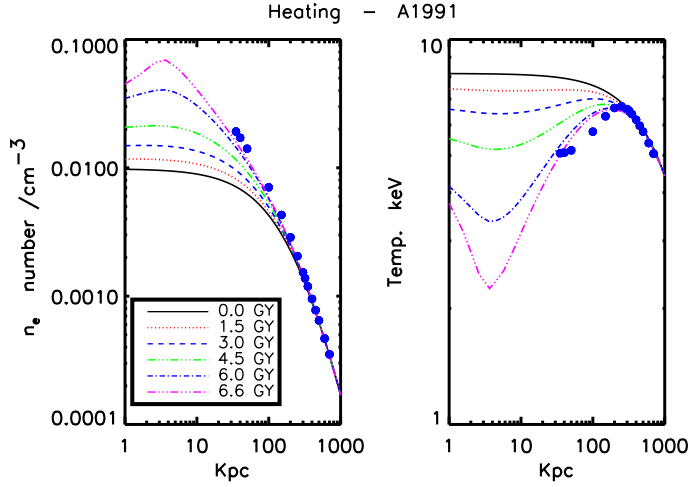


Fig. 6. Model D, cooling with heating: the simulated gas density and temperature profiles as functions of radius. The big dots represent the observations

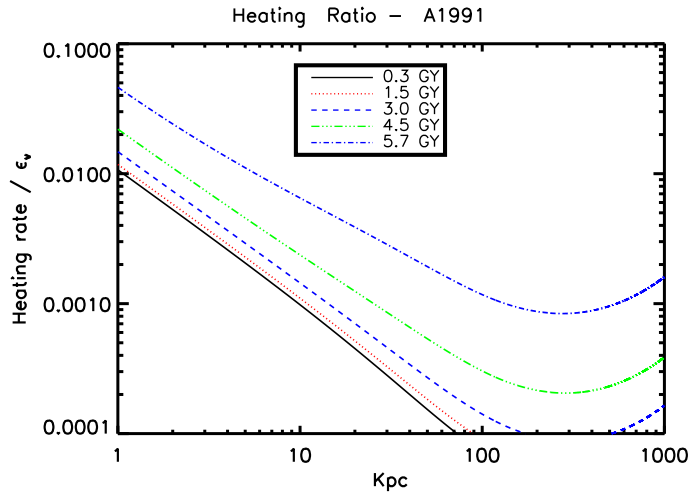


Fig. 7. Model D ($r_o = 44$ kpc): the plot of the ratio between the heating rate and cooling rate ($\mathcal{H}_v / \epsilon_v$). With increasing the the cutoff radius r_o , the heating profile becomes more smoother.

ture at the center is higher than observed. With the large cutoff radius r_o , the heating profile can balance the cooling but it becomes an artificial model which is not physical. In other words, the gradient of the heating profile becomes near to the gradient of the X-ray emissivity, ensuring the balance between the heating and cooling.

4.5. The effect of the heating on cooling time scale

In some cooling flow clusters, the observed cooling time scale is very short, in the range of 10^8 yr to 10^9 yr, but the cooling gas below 1-2 keV is not observed. This result is interpreted as indication that there must be a heating mechanism to stop the cooling. In figure 8, The cooling time scale is very short in the center, even there is no catastrophic cooling or there is no much cooling. Figure 9 show that the heating increases the cooling time scale. If the cluster was heated, then we should find that the cooling time scale must be higher than observed.

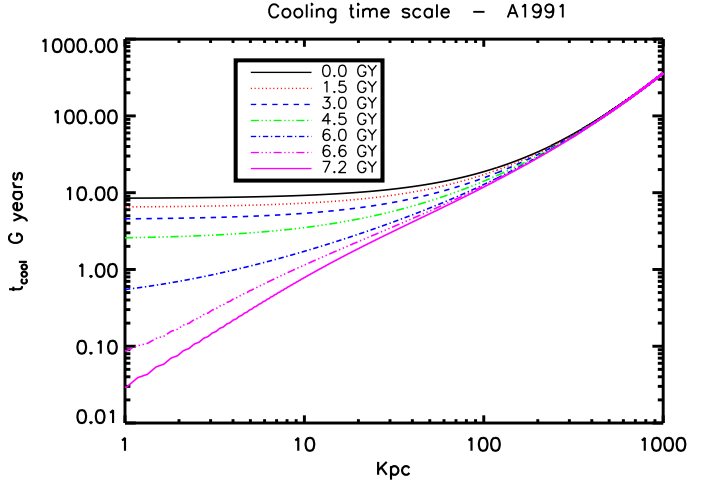


Fig. 8. Model A, pure cooling: the cooling time scale is very short in the center, even there is no much cooling.

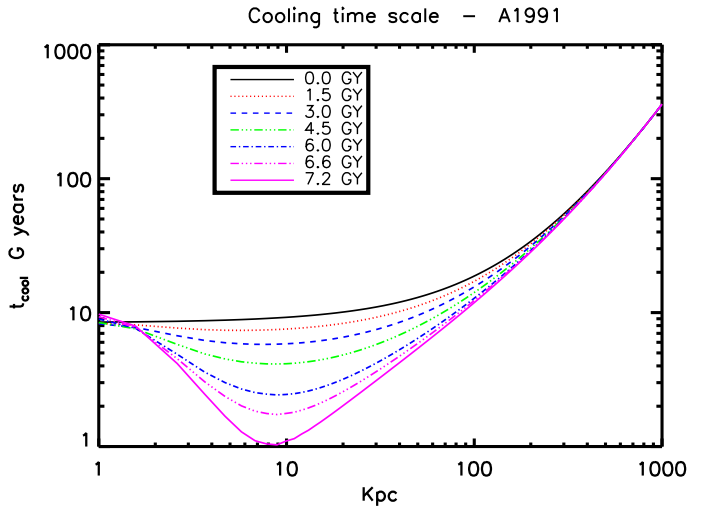


Fig. 9. Model B: the cooling time scale is higher than pure cooling simulation. In the center, the cooling time scale is higher than observed which is against the heating of cluster.

5. Summary and conclusion

We have carried out time dependent simulations with cooling and heating. The general result is that the best fit to the observations is the model without heating (model A). The effervescent heating is a function of the ICM pressure gradient but the cooling is proportional to the gas density square and square root of the gas temperature. Furthermore, the conclusions are :

- 1- From our simulations, the cooling can not be a steady flow as assumed by standard cooling flow model. The gas density must increase with the time; i.e the ICM must be compressed under the force of the inflowing gas.
- 2- The effervescent heating model profile (without the smoothness function) is more steeper than the radiative cooling profile, which makes it is very difficult to balance the cooling.
- 3- The function $1 - e^{-r_o/r}$ is not a cutoff function but it is a smoothing function in order to control the steepness of the

heating function letting it balance the radiative cooling; i.e. it is an artificial model.

4- At inner radius close to the realistic value of the accretion radius (model D), the accretion mass rate due to flowing gas is not enough to fuel the black hole in the center of cluster. It's not reasonable to set the accretion radius of the black hole at large radius, (for example 1-1.5 kpc, as used for the three dimension simulations).

5- In some cooling flow clusters, the observed cooling time scale is very short, in the range 10^8 yr to 10^9 yr, but the cooling gas below 1-2 keV is not observed. This result is interpreted as indication that there must be a heating mechanism to stop the cooling. As in figure 8, the cooling time scale inside a radius of 10 kpc is shorter than 1 Gy but there is no a cool gas. Moreover, from our simulations (model B), we found that the heating process increases the cooling time scale. If cooling time scale is a good approximation for the actual cooling time and the cluster is heated, then we must find that the cooling time scale is larger than observed.

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